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PRELIMINARY INVESTIGATION OF WELDING TECHNIQUES FOR THE CONCRETE INTEGRATED CONTAINER (CIC) LID TO BODY CLOSURE WELD

Report No. 90-263-H

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ABSTRACT

This report describes the results of a preliminary investigation of welding techniques and issues relating to the lid to body closure weld of the Concrete Integrated Container (CIC).

The investigation of welding processes was concentrated primarily on experimentation with Flux-Cored Arc Welding (FCAW) and Metal-Cored Arc Welding (MCAW) because they can be mechanized or automated and have relatively high metal deposition rates. Another process, Submerged Arc Welding (SAW) is currently being evaluated however this work is beyond the scope of this report.

A horizontal fillet/groove weld joint design, which is suitable for remote welding, and acceptable for ultrasonic inspection, has been established for the CIC closure weld. FCAW and MCAW procedures have been established for both the full-scale and 1/2-scale CIC closure weld geometries. As a result of this work a FCAW procedure has been selected for the 1/2 scale CIC, however the selection of the welding process for the full-scale production CIC's awaits the completion of the SAW trials.

Future work will concentrate on the development of remote or automated welding and inspection techniques.

job	file	date	report no.
81-181-461	823.41	December 5, 1990	90-263-H

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EXECUTIVE SUMMARY

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Metallurgical Research Department

As part of OHRD's technical assistance to the Nuclear Engineering Department, D&D-Gen in the Concrete Integrated Container (CIC) Program, the Metallurgy Section carried out a preliminary investigation of welding techniques and issues relating to the lid to body closure weld. This report highlights the current status of the research effort to develop closure weld specifications for the full scale production CIC's and documents the changes made to the closure weld design as a result of this work.

The investigation of welding processes was concentrated primarily on experimentation with Flux-Cored Arc Welding (FCAW) and Metal-Cored Arc Welding (MCAW) because they can be mechanized or automated and have relatively high metal deposition rate. Another process, Submerged Arc Welding (SAW), is currently being evaluated however, this work is beyond the scope of this report.

A horizontal fillet/groove weld joint design, which is suitable for remote welding, and acceptable for ultrasonic inspection, has been established for the CIC closure weld. Although the welding process to be used for the full-scale production CIC's has not yet been selected, FCAW and MCAW procedures were developed for both the full-scale and 1/2-scale closure weld geometries. As a result of this work it has been recommended that, for the CIC 1/2-scale model, the closure weld will be made with manual FCAW. The selection of the welding process for the full scale production CIC's awaits the completion of the SAW trials.

Future work will evaluate the mechanical properties of representative full scale fillet/groove welds, determine the techniques required for remote bead placement, and document in detail the requirements for the production welding work station.

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PRELIMINARY INVESTIGATION OF WELDING TECHNIQUES FOR THE CONCRETE INTEGRATED CONTAINER (CIC) LID/BODY CLOSURE WELD

P.Y.Y. Maak & J.G. Galloway

1.0 INTRODUCTION

The concrete integrated container (CIC) is being considered as an option to store used fuel when Pickering NGS's existing bays are full. An on-site storage period of approximately 50 years is envisioned. The CIC is also designed for future transportation of used fuel to permanent disposal sites. Two welding facilities are anticipated for the final closure welding of the CIC, which would be located at the Pickering AIFB and the "B" Primary IFB. Each welding facility should be capable of handling 40 CIC's per year. Following the final closure welding, an ultrasonic inspection of the CIC closure weld will be performed. The Metallurgical Research Department has been carrying out a comprehensive work program to develop welding, inspection and auxiliary systems for the final closure of the CIC/1/.

1.2 Closure Welding of the CIC and the 1990 Work Program

The schematic design of the CIC is shown in Figure 1. The present final closure weld joint designs consist of either a 32-mm-thick full penetration groove weld or an equal-strength fillet weld in CSA 300WT steel, which have a total length of over 9000 mm or 29 feet. For the development of closure welding and inspection facilities, the following planning assumptions have been made:

- the necessary work station equipment must be specified for tendering in early 1992;
- the closure welding and inspection must be performed remotely to minimize man-rem exposure;
- closure welds with acceptable quality must be made with high reliability;

- the closure welding of each CIC is required to be completed within one shift (ie 8 hours)

The 1990 work program is financially supported by the Nuclear Engineering Department (NED), D&D-GEN and the Metallurgical Research Department. The program was divided into the following phases:

Phase 1 - Evaluation of lid closure assembly design and associated closure weld closure weld joint design.

The NED and OHRD technical personnel reviewed and selected the best lid closure assembly, which was most suitable for remote inspectionand remote welding applications. Welding studies were performed on the associated weld joint designs.

Phase 2 - Assessment of flux-cored arc welding (FCAW) and metal-cored arc welding (MCAW) techniques.

FCAW and MCAW studies were carried out by the technical personnel of Metallurgy Section at OHRD. The feasibility of fabricating a sound horizontal groove and fillet/grove weld remotely was investigated.

Manual FCAW and MCAW procedures will be developed by the technical personnel of Metallurgy Section. A field welder will be trained at OHRD, who will perform the final closurewelding of the half-scale CIC. The half-scale CIC will be tested by the Mechanical Research Department in 1990 and the test results will be used by the NED technical personnel to obtain a transportation license from the Atomic Energy Control Borard in 1990.

Phase 3- Assessment of submerged arc welding (SAW) techniques.

SAW studies will be carried out at the Welding Institute of Canada (WIC) by technical personnel of Metallurgy Section and by WIC personnel. The feasibility of fabricating sound horizontal fillet welds remotely will be evaluated. These test results will be compared with the FCAW and MCAW test results.

Phase 4 - Ultrasonic inspection studies.

Based the welding development test results, a specific weld joint design was selected for the final closure of the CIC. Ultrasonic inspection studies will be carried out by the technical personnel of the Advanced Systems Technology Section of the Metallurgical Research Department to investigate the ultrasonic inspectability of this weld joint design. A manual inspection procedure will be developed for inspection of the half-scale CIC in 1990.

Phase 6 - Evaluation of weld surface machining/milling equipment and techniques.

Commercially available weld surface machining/milling equipment will be tested. The machining/milling speed and weld surface finish will be evaluated. Machined samples will be used for ultrasonic inspection studies.

2.0 EXPERIMENTATION

2.1 Welding Equipment and Welding Consumables

All the welding trials were carried out using the Airco "Pulse Arc 500" welding machine. This system could be used for continuous wire welding (i.e FCAW and MCAW) studies. It allowed for both constant voltage (non-pulsed) and pulsed-current (P-current) FCAW and MCAW. For mechanized welding studies, the welding torch travel was controlled by utilizing a motorized carriage/track system.

High toughness carbon steel of CSA G40.21-300WT specifications (impact tested to category A of Table 10A, CSAG40.21) has been chosen for the CIC steel liners. This material was, however not available for the present study. The present welding trials were carried out on 16-mm-thick and 32-mm-thick carbon steel plate of SA 516 Gr 70 specification, which is believed to respond similarly in terms of process operation.

For FCAW studies, the 1.2 and 1.6 mm diameter Hobart FabCo 803 filler metal and 1.6 mm diameter Corex Verti-Cor filler metal were selected. These filler metals conform to AWS A5.29-80 class E81T1-Ni2. For MCAW studies, the 1.6 mm diameter Hobart Fabloy 2N wires were used, which conform to AWS A5.28 class E80-Ni2. The chemical composition and mechanical properties of these wires are shown in Table I. Both wires satisfy the minimum Charpy V-notch impact values of 20J at -45 C, (based upon manufacturers qualifications) as they are formulated for good weld metal impact properties at low ambient temperatures. Larger diameter wires of both classifications would have been considered for this project, however they were not readily available from any known manufacturer.

2.2 Lid Closure Assembly and Closure Weld Joint Designs

Two lid closure assembly designs were considered for the CIC, type A and type B (see Figures 2 and 3). The type A lid assembly design employs a horizontal groove weld joint. It was percieved to be difficult to obtain acceptable weld joint fitup with this lid assembly. The type B lid assembly design can employ both a horizontal groove weld and a fillet (fillet/groove) weld in a lap weld joint. Better weld joint fitup and significant savings in machining cost could be obtained by using the lap weld joint employed in the type B lid assembly design. A preliminary evaluation of this joint design from an ultrasonic inspectability standpoint indicated that it would lend itself more readily to remote inspection. Because of the above mentioned advantages, type B lid closure assembly design was selected for further development/2/.

The original final closure joint design for the CIC called for a full penetration groove weld with an effective throat thickness of 32 mm. The fillet weld and the fillet/groove combination weld

must also contain the effective throat thickness of 32 mm. The definitions of effective throat thickness and theoretical throat thickness of these weld joints are shown in Figure 4. Furthermore, the theoretical throat thickness, which can be achieved in the various fillet and fillet/groove weld joint designs are shown in Figure 5.

2.3 Welding Trials

2.3.1 Bead-On-Plate Welding Trials

For continuous wire welding processes such as FCAW and MCAW, stable spray metal transfer is desirable for producing satisfactory fusion characteristics and sound welds. In comparison to constant voltage (CV) or non-pulsed current welding, it is generally known that pulsed current (P-current) welding promotes spray metal transfer and improved out-of-position welding capabilities.

In the present work, horizontal bead-on-plate weld tests were carried out to determine the usable operating current range for each filler metal under study, within which stable and spray metal transfer could be achieved. Both CV and P-current welding techniques were applied in these weld tests.

2.3.2 Horizontal (2G) Groove Welding Trials

As mentioned in Section 2.2, the type B closure lid assembly could employ both horizontal groove weld joint design and the horizontal fillet (fillet/groove) weld joint designs. In the present work, a limited number of manual and mechanized groove welds were made in the horizontal (2G) welding position in both 16-mm-thick and 32-mm-thick plates. The typical manual FCAW conditions and deposition sequence for horizontal groove welding in 32-mm-thick plates are shown in Table II.

2.3.3 Horizontal Fillet and Fillet/Groove Welding Trials

One of the main objectives in the present work was to develop manual FCAW and MCAW techniques for the final closure welding of a half-scale CIC. Fillet and fillet/groove welds were made in 16-mm-thick carbon steel plates in the horizontal position using both manual FCAW and MCAW techniques. The welding conditions and test results are shown in Table III.

Fillet and fillet/groove welds were made in 32-mm-thick using the mechanized the FCAW and MCAW processes. The test parameters and results are shown in Table III.

3.0 EXPERIMENTAL RESULTS

3.1 Welding Characteristics of FCAW Wires

Bead-on-plate weld tests were carried out in the horizontal welding position using the Hobart

FabCo 1.2 and 1.6 mm diameter filler metal. The test results indicated that stable and spray metal transfer could be obtained over a wide range of usable operating current in the CV and P-current welding modes. As compared to the CV mode, the P-current mode appeared to promote higher wire burnoff rates and thus higher weld metal deposition rates (Figure 6 and Figure 7). The 1.2 mm diameter filler metal had an usable operating current of 150 to 240 A (Figure 6). At welding current levels higher than 240 A, some arc instability was observed. The Airco wire feeder had difficulties producing the extremely high wire feed rate required to maintain stable welding conditions. The 1.6 mm diameter filler metal had a wider usable operating current of 180 to 300 A in the CV welding mode (Figure 6). For welding current levels lower than 180 A, the metal transfer became globular and unstable. When the P-current mode was used, stable and spray metal transfer could be extended down to 150A (Figure 6).

For multipass groove and fillet/groove welding, it was shown that high welding current levels in the range of 210 to 300 A were required to produce high weld metal deposition rates and thus relatively short joint completion time. The 1.6 mm diameter filler metal, which had a wider usable welding current range, was thus preferred for the CIC welding application. It was found in the present work that in comparison to the P-current welding mode, the CV welding mode promoted better control of the weld pool and thus better weld bead profile in the horizontal welding position at high current levels (>240 A). Despite the higher weld metal deposition achievable in P-current welding mode, the CV welding mode was preferred for the CIC closure welding application. As shown in Figure 7, high weld metal deposition rate of 8 to 14 lb/hr (3.6 to 6.4 Kg/hr) could be obtained with FCAW in the CV welding mode (ie current range of 210 to 300A).

In the present work, weld tests were carried out with C25 (75%Ar25%CO_2) shielding gas using the Hobart FabCo filler metal and the Corex Verti-cor filler metal. Both wires displayed similar fusion and welding characteristics. The T-1 (acid) slag system displayed the fast freezing characteristics. The weld pool was supported by the slag on the weld surface. Well shaped and fully fused beads with good slag detachability could be easily obtained in the horizontal welding position. After each weld pass, the slag could easily be removed by either using the metal wire brush or needle descaler.

The test results indicated that the horizontal groove welds and the horizontal fillet/groove welds, which were made using the Hobart FabCo wire, were susceptible to "wormhole" surface porosity. These discontinuities were not found in welds which were made using the Corex filler metal. They appeared to form as a result of gases escaping under the rapidly freezing slag layer, forming elongated depressions or wormhole porosity the surface of the weld. The formation of these marks was, however, readily detectable immediately after welding. It was noticed that these wormhole marks were remelted by the subsequent weld passes. Metallurgical examination of cross sections of completed welds indicated no observable gas porosity in the weld metal. Welding conditions such as current and travel speed had no apparent effect on the formation of these discontinuities.

3.2 Welding Characteristics and Weld Quality of MCAW Filler Metal

For the 1.6mm diameter Hobart FabLoy MCAW filler metal, stable and spray metal transfer could be obtained in the current range of 180 to 300 A using the P-current welding mode (Figure 6). The CV welding mode promoted globular metal transfer and high weld metal spatter levels at all current levels. For MCAW, the P-current welding mode was recommended for the CIC welding application. The recommended shielding gas is C8 (92%Ar8%CO_2).

In comparison to FCAW, MCAW appeared to produce a more penetrating welding arc under the same welding conditions. Only a small number of slag islands were found on the weld surface. The weld bead tended to be more convex because of the absence of the slag to support the weld pool. The glass like slag islands could only be removed by using needle descaler, and could not be removed using the wire brush, however the slag volume created is only a fraction of that produced by the FCAW process.

3.3 Horizontal Groove FCA Welding

A number of groove welds were made in the horizontal welding position (2G) using the Hobart FabCo 1.6 diameter filler metal and the manual welding technique. The cross sections of two groove welds in 16-mm-thick plates are shown in Figure 8. The cross section of a horizontal groove weld in 32-mm-thick plate is shown Figure 9. The welding conditions and weld bead deposition sequence is shown in Table IV. In general, these groove welds displayed satisfactory weld quality. The welding operator had to carefully maintain the proper drag angle and work angle of the welding torch in order to avoid slag entrapment. Slag entrapment was found in the root pass of the 16-mm-thick welded sample (Figure 8a). Definitions of drag angle, push angle and work angle are shown in Figure 10. During the horizontal groove welding, the molten weld pool tended to flow ahead of the weld and flow downward in the direction normal to the direction of travel. Proper torch drag angle must be used to prevent the weld pool running ahead of the welding arc which might cause arc instability in slag entrapement. Proper torch work angle was also required to prevent excessive weld bead rollover (which might also cause slag entrapment), and to optimize weld penetration.

Two mechanized groove welds were produced. The welding torch was carried by a motorized carriage. This simple mechanized welding equipment setup allowed no adjustment of the welding torch position during welding. These mechanized groove welds contained a large amount of slag entrapment and were considered to be unacceptable.

3.4 Horizontal Fillet and Fillet/Groove Welding Trials

Horizontal fillet and fillet/groove welds were made using the 1.6 mm diameter Hobart and Corex FCAW filler metal. The CV welding mode was used in these welding trials. The C25 shielding gas mixture was used. A needle descaler was used for removal of the slag (see Figure 11). This air powered device is designed for weld de-slagging, using rapid impacts of multiple needles onto

the weld surface, and could be mechanized providing that the holding system is robust and there is provision made for removing the debris.

3.4.1 Manual FCA and MCA Welds in 16-mm-thick Plates

A fillet weld and four fillet/groove welds were made in 16-mm-thick plates using the manual FCAW technique. The welding conditions of these welds are shown in Table V.

It was shown that the top edges of the weld joint for weld samples F1, F2 and F3 were melted off (see Figures 12a, 12b and 12c). An extra weld pass was placed in weld sample F4 to rebuild the top edge. Furthermore, all the weld samples displayed little or no root penetration. This meant that the effective throat thickness would be the same as the theoretical throat thickness (Figure 4). In other words, weld joints employing 0° and 10° bevel angles would never attain the desirable effective throat thickness of 16mm. With a joint bevel angle of 20°, weld sample F4 acquired an effective throat thickness of 15.5 mm, which was equivalent to the theoretical throat thickness (see Figure 12d). Lack of root fusion was found in weld sample F3, which employed a weld joint of 35° bevel angle (see Figure 12b). Weld sample F5 was made using the same welding conditions as weld sample F4. Weld sample F5 contained weld start and stop areas in the mid-length of the weld. No grinding of the weld start and stop areas was performed. This sample will be inspected using the ultrasonic inspection technique. The test results will be used to assess whether grinding is required to avoid weld defects in the weld start and stop areas. The results are not available at the time of preparation of this report.

For weld samples F1, F2 and F3, two capping passes were made using welding current at 240 A and a welding speed of 300 mm/min (12 in/min). The weld surface was ropy and sharp angles were found at intersecting weld beads (Figures 12a, 12b and 12c). For weld sample F4, three capping passes were made using the same welding current at 240 and slightly higher welding speed at 360 mm/min (14in/min). Furthermore, these weld passes were more closely spaced. The weld surface of weld sample F4 was much more flatter and had shallower valleys between the weld beads (Figure 12d).

Weld sample F6 and F7 were made in 20° beveled weld joints using the manual MCAW technique. The welding conditions and measured effective throat thickness are shown in Table III. A total of six weld passes was required to make these welds.

Weld sample F6 was made with no slag removal. For weld sample F7, the surface slag was removed once after the third weld pass. As shown in Figure 13, a larger amount of slag islands were found on F6 than on F7. The test results indicated that after three weld passes, the accumulated slag started to interfere with welding arc and cause excessive weld spatter and unstable metal transfer. The cross section of weld sample F7 was shown in Figure 14 and no slag inclusions were found. These test results indicated for MCAW slag removal could be performed after three or more weld passes. Weld sample F7 displayed an effective throat thickness of 15.7mm. The test results confirmed again that it was feasible to marginally achieve the minimum effective throat thickness of 16 mm using a 20° beveled weld joint.

3.3.2 Mechanized FCA and MCA Fillet and Fillet/Groove Welds in 32-mm-thick plates

A total of three fillet and fillet/groove welds were made using the mechanized FCAW process. The welding conditions are shown in Table III, Table IV and Table V. The cross sections are shown in Figure 15 and Figure 16.

Effective throat thicknesses of 22 mm and 28 mm were found in weld sample F8 (0° beveled weld joint) and weld sample F9 (10° beveled weld joint) respectively. Weld sample F10, which employed a 20° beveled weld joint, displayed an effective throat thickness of 32 mm.

All the FCA fillet and fillet/groove welds displayed good weld quality in a single cross-section. The detailed welding conditions for weld sample F10 are shown in Table IV. High welding current at 300 A was used for all the weld passes to achieve fusion. For the fill passes, relatively low welding speed of 300 mm/min (12 in/min) was used to achieve a large bead size. For the capping passes, a higher welding speed of 460 mm/min 18 (ipm) was used to achieve optimum weld pool control (smaller beads) and thus a smooth weld surface (see Figure 16).

Weld sample F11 (20° beveled weld joint) was made using the mechanized MCAW process. The detailed welding conditions are shown in Table V. This weld sample displayed an effective throat thickness of 33.5 mm. The weld sample displayed sound weld quality and deep root penetration (see Figure 17). In comparison to FCAW, it was shown that deeper root penetration could be achieved with MCAW. A welding current of 300 A was used for all weld passes. For the fill passes, welding speeds of 250 to 300 mm/min (10 to 12 in/min) were used. For the last two weld layers, a higher welding speed of 360 mm/min (14 in/min) was used to achieve good weld pool and weld bead profile. As shown in Figure 17, the weld surface of the MCAW sample F11 appeared to be more ropy than the FCAW sample F10. For horizontal fillet/groove welding, this relatively irregular surface had no adverse effects on the weld quality.

In comparison to horizontal groove welding, the weld beads were well supported in horizontal fillet and fillet/groove welding. It was shown that sound FCA and MCA fillet and fillet/groove welds could be made using the simple mechanized welding setup. A fixed welding torch position (ie work angle of 45° and drag angle of 30°) was used for all weld passes, however, the ability to change the torch work angle for various weld passes is essential for optimum weld penetration, especially for fillet/groove joints.

4.0 DISCUSSION

4.1 CIC Closure Weld Joint Design

The present work had clearly shown that in comparison to the horizontal groove weld joint design, the horizontal fillet/groove weld joint design was more suitable for remote welding applications and is the preferred weld joint design for the final closure of the CIC. For horizontal fillet/groove welding, the requirements for accurate weld bead placement and weld pool control were found to be not as stringent as compared to horizontal groove welding. Futhermore, it was

shown that higher degree of weld bead rollover could be tolerated in horizontal fillet/groove welding. This indicates that a higher welding current and higher deposition rate could be achieved in horizontal fillet/groove welding. The occurence of slag entrapment and lack-of-fusion defects was anticipated to be lower in horizontal fillet/groove welding. It is perceived that CIC closure welds with acceptable weld quality could be made more consistently and with higher joint completion rates by employing the horizontal fillet/groove weld joint design.

It was shown that for lap joints with tight fitup (i.e. <1mm upper plate offset), the effective throat thickness of 32 mm could be achieved using a 20° beveled fillet/groove weld joint. It is anticipated that provided the current tolerences for plate flatness (<2mm) are met, this effective throat thickness will be achievable. Any increase in upper plate offset over 2mm may however require an increase in the bevel angle to maintain the 32mm effective throat.

4.2 Weld Quality and Joint Completion Rate

Lack-of-fusion defects, slag entrapment and excessive gas porosity are defects commonly found in multipass welds. These defects are normally located between the weld passes and in the weld start and stop areas. It was shown in the present work that mechanized FCA and MCA fillet/groove welds of excellent weld quality could be made using high welding current (up to 300 A) and high welding speed (up to 460 mm/min or 18 ipm) welding parameters. The use of high current/high welding speed welding parameters appeared to promote minimal occurance of lack-of-fusion defects, including the weld start and stop areas. In fact, the test results appeared to indicate that the grinding procedure of weld start and stop areas may possibly be eliminated, pending verification through ultrasonic inspection.

For FCAW and MCAW, an irregular weld surface with large valleys between neighbouring weld beads has been shown in previous work to cause slag entrapment between the weld passes. The present test results showed that excellent weld bead profile of FCA and MCA horizontal fillet/groove welds could readily obtained, which minimizes the risk of slag entrapment. The slag inclusions and inadequate fusion found in some of FCA and MCA welds appeared to be caused by improper weld bead placement and/or improper torch work angle. By improving the weld bead placement techniques, the occurence of defects could likely be significantly reduced.

Among the various FCAW and MCAW filler metal used in the present work, only the Hobart FabCo filler metals were found to be susceptable to wormhole surface porosity. This wormhole porosity is known to be a defect commonly found in FCA welds, which were made using the Ar-CO_2 shielding gas mixture/3/. It was suggested that a potential source of gaseous contamination was the lubricant used in the wire drawing process. It was claimed /3/ that the incidence of this effect might be reduced, by increasing the contact tip to workpiece distance to within the range of 25 to 30 mm. Under these conditions the enhanced preheating of the wire would help the lubricant to burn off. In the present work, the contact tip to workpiece distance was held at a distance of 20 to 25 mm. The welding trials also indicated that the occurance of wormhole porosity might be reduced by using a larger gas cup, although this did not entirely resolve the problem. For the Hobart FabCo FCAW wire, the reason for the formation of the wormhole

porosity has not yet been identified. The effects of the welding conditions (eg contact tip to work distance and welding speed etc) should be closely examined in the future. It is also possible that only one lot or batch of a manufacturer's product would produce this effect.

Based on the number of weld passes and the welding speed used to fabricate weld sample F10 and weld sample F11 (see Tables VI and VII), the total arc-on time for completion of a full-scale CIC closure weld was estimated at about 13.0 hours for FCAW, and 13.6 hours for MCAW. Other non-welding time for slag removal, weld surface examination, and resetting of the welding torch after each weld pass must be added to arc-on time. The ratio of the arc-on time to the joint completion time is called the operator factor. For mechanized FCAW and MCAW, operator factors in the range of 70 to 80% are anticipated. This means that the joint completion time for the final closure of the CIC would be about 16.3 to 18.6 hours for FCAW and 17.0 to 19.4 hours for MCAW. If two welding systems are used, the estimated joint completion time would be about 8.2 to 9.3 hours for FCAW and 8.5 to 9.7 hours for MCAW. This is an optimistic estimation since two welding systems would add considerable complexity to the final closure welding system. The present results appear to indicate that it would be impossible to complete the final closure welding of the CIC in one shift (ie 8 hours). It is proposed that an overlapped work schedule for loading used fuel into the CIC and final closure welding operation should be considered.

4.3 Half-Scale CIC Closure Welding

The test results indicated that it will be feasible to fabricate sound half-scale CIC closure welds using either the manual FCAW technique or the manual MCAW technique. Proper weld deposition sequence and techniques were developed, which could be transferred to a field welder. An Ontario Hydro structural FCA welding procedure SA-538 had previously been qualified, which could be used for the final closure of the half-scale CIC. In this procedure, high welding current level of 280 to 300 A were employed for the fill passes. The present work indicated that lower welding current levels of about 240 A were preferred to achieve optimum control of weld pool weld bead profile, and operator comfort. This will require a revision to SA 538 on the welding data tables.

It was shown that for the 20° beveled fillet/groove weld joint, an effective throat thickness of 15.5 to 15.7 mm could be achieved using the manual FCAW and MCAW technique respectively. In order to achieve the required throat thickness of 16 mm, a fillet/groove with larger bevel angles (ie 23° to 25°) would be required.

5.0 OTHER ON-GOING STUDIES FOR 1990

5.1 Remote Weld Bead Placement Techniques

It has been shown in the present work that proper weld bead placement is essential to ensure sound weld quality. It is perceived for the final closure welding of the CIC, it is necessary to adjust the welding torch position during welding in order to achieve optimum weld bead

placement. Ideally, the closure welding system for the CIC should be equipped with a laser-based sensor system which would provide the capability for automatic tracing of the weld joint and weld bead location for each weld pass. This data would then be used for automatic weld bead placement. While this technology is at hand (research is currently ongoing within the Metallurgical Research Department for automated seam tracking with a commerical laser-sensor), it is not certain whether the necessary interfacing and implementation can be reliably achieved for the CIC application within the existing constraints of schedule and available manpower. Therefore, it is necessary to define a somewhat simpler approach which can be achieved within the necessary timeframe.

The Metallurgical Research Department has developed a portable robotic welding system, which can be used for repair of cavitation damage of hydraulic turbine runners/4/. A short program will be carried out in 1990 to investigate automatic weld bead placement with the use of this robot. The robot will be used to track the root or corner of the fillet weld joint. The desirable weld path for the root pass will be determined. Root pass welding will be carried out automatically based on the recorded weld path. Based on the weld path data of the root pass, the weld paths for subsequent weld passes will be determined mathematically by the controller of the robot. Subsequent weld passes will be carried out following the predetermined weld paths. It is perceived that this bead placement technique will accommodate variations of weld paths caused by factors such as weld joint/track misalignment.

In multipass welding, it is necessary to adjust the placement of the weld bead during welding according to the actual location and profile of the previous layer of weld beads. This would be based on remote camera viewing of the weld joint and welding arc, with torch position operator-adjusted as required, ie via a joystick.

The assembly of a remote mechanized welding system is in progress. A remote arc viewing camera system, which was custom built by the U.S. company, Magnatech, will be used to monitor the welding arc and the weld joint area immediately in front of the welding arc. According to what is seen, the welding operator will adjust the welding torch position via a joystick for optimum weld bead placement.

In the present proposed approach, the crude weld path will be determined by the robot. Fine adjustments of the welding torch position will be carried out by the operator through remote arc viewing via a joystick.

5.2 Submerged Arc Welding Studies

Submerged arc welding (SAW) is being considered as an alternative closure welding process for the CIC. SAW studies are being carried out at the Welding Institute of Canada (WIC), in Oakville. The SAW trials will be performed by OHRD's personnel and by the WIC's personnel. The weld quality, joint completion rate and suitability of remote welding of SAW will be assessed and compared to FCAW and MCAW processes.

5.3 Mechanical Evaluation of Welded Joints

An evaluation of weld metal toughness will be conducted at -45° C, as is required for base metal qualification, using the standard Charpy impact test. The minimum absorbed energy value at this temperature for the specified CSA G40.21-300WT steel is 20J. Testing will be carried out on representative weld deposits with the welding parameters (ie heat input) as specified in this study for full scale containers using both flux-cored and metal-cored filler wires in SA516 Gr70 steel.

Future work is planned to evaluate the toughness of the heat-affected-zone in representative full scale fillet/groove welds in CSA G40.21-300WT steel, when this material becomes available.

5.4 Ultrasonic Inspection Studies

The Advanced Systems Technology Section is presently carrying out ultrasonic inspection studies on fillet/groove weld joints. Initial test will be carried out on machined carbon steel plates, which simulate the fillet/groove welds. The reflecting surflace will be machined to different angles. Small diameter holes will be introduced into steel plates to simulate weld defects.

The test results will be used to assess the ultrasonic inspectability of the fillet/groove welds, the requirements of machining accuracy of the reflecting surface and the requirements of the UT inspection equipment for the final closure inspection system.

5.5 Weld Surface Preparation Techniques

Precise weld surface preparation of closure fillet/groove weld is essential for automated ultrasonic inspection. Preliminary studies showed that it is possible to machine the surface of fillet welds (32-mm leg size) at 45 degrees in a single pass using a high speed shear cutter. A surface finish of Ra 125 (~.003 mm) was obtained, which was considered to be acceptable for ultrasonic inspection. Curved weld samples are being prepared, which will be sent to an Ontario company (Prodomax Industrial Automation) for further machining tests. The surface finish of these curved samples and machining accuracy will be assessed.

6.0 CONCLUSIONS

6.1 It is feasible to perform the final closure of the CIC using the FCAW and MCAW processes. It has been demonstrated that closure welds of acceptable weld quality can be made in the horizontal welding position if the weld joint design, filler metal and welding parameters recommended in this study are used.

6.2 The most suitable final closure weld joint has been identified to be a horizontal fillet/groove weld in a lap joint. In order to achieve the minimum effective throat thickness of 32 mm, the weld preparation should be beveled to a minimum of 20°.

6.3 Welding trials have indicated that it will be impossible to complete a production

6.3 Welding trials have indicated that it will be impossible to complete a production closure weld within the timeframe of one shift (8 hrs) using either the MCAW or the FCAW process. Current estimates for a full-scale CIC closure weld is 17.0 to 19.4 hours for MCAW and 16.3 to 18.6 hours for FCAW using one welding system.

6.4 Both the Hobart and Corex FCAW filler metal display excellent fusion and welding characteristics. The surface slag can be removed by using the wire brush or a needle descaler. In comparison to the pulsed-current welding mode, the constant voltage welding mode is preferred for optimum weld pool control. For horizontal fillet/groove welding, high deposition rate of 8 to 14 lb/hr (3.6 to 6.4 kg lhr) can be achieved using 1.6 mm diameter filler metal.

6.5 The Hobart FCAW filler metal used was susceptable to wormhole surface porosity. This porosity appears to be remelted by subsequent weld passes. The Corex FCAW filler, however was not susceptible to this kind of porosity discontinuity.

6.6 The Hobart MCAW filler metal exhibits comparable excellent fusion characteristics. Under the same welding conditions, deeper root penetration can be obtained in MCAW than in FCAW. Stable and spray transfer can only be obtained in the pulsed-current welding mode. Only scattered slag islands are found on the weld surface. After two to three weld passes, excessive slag build-up may interfere with welding arc stability. Slag can be removed using a needle descaler. In comparison to FCAW, MCAW produces a smaller volume of slag.

6.7 Manual FCAW and MCAW procedures and welding techniques have been developed, which can be transferred to a field welder for the final closure of the half-scale CIC.

6.8 It has been demonstrated that sound horizontal fillet/groove welds can be made using both mechanized FCAW and MCAW. For remote closure welding, it has been shown that proper remote welding techniques must be developed to ensure optimum weld bead placement and thus acceptable weld quality. Preliminary studies on a remote weld bead placement techniques using a custom-built robot and a mechanized welding setup with remote camera viewing and joystick control are in progress.

7.0 RECOMMENDATIONS

7.1 1/2-Scale Mockup Manual Closure Welding

The present study indicates that using either the FCAW or the MCAW process would be acceptable for the final closure of the 1/2-scale CIC model. The use of the FCAW process is recommended however because this process has previously been qualified for use as Ontario Hydro structural welding procedure SA-538. The recommended filler metal for this procedure is 1.6mm diameter Corex Verti-Cor 81Ni2. The following welding parameters are recommended for a 20° preparation fillet/groove lap joint in 16mm plate:

- Shielding Gas >C25(75%Ar25%CO_2)
- Flow Rate >16 - 18L/min (35 to 40 cfh)
- Current Range >220-270 Amperes
- Voltage Range >24-27 Volts
- Wire Feed Speed >65-90 mm/sec (154-213 ipm)

7.2 Revisions to SA 538

Some revisions to SA 538 are recommended to update the welding data table with the information gained in the present work.

ACKNOWLEDGEMENTS

The authors wish to express their thanks to the technical personnel of the Advanced Systems Technology Section of OHRD for performing the assessment of the closure weld joint designs and for carrying out the ultrasonic inspection studies. Thanks are also extended to Mr. K. Chan of the Advanced Systems Technology and Mr. P. Stearns of Divisional Services for evaluating of weld surface machining/milling equipment. Mr. R. Halliday and Mr. G. Schaller of Sandvik Canada Inc. are also acknowledged for performing preliminary weld surface milling test. The editorial contributions of Dr. W.H.S. Lawson of the Metallurgy Section and Mr. D. Ribbans and Mr. S. Smith of the Nuclear Engineering Department are also acknowledged.

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REFERENCES

1. D.J. Ribbans, R. Sumar and J.F. Tanaka, IFTU memo #248 "Scope of Work - Concrete Integrated Container, Welding Facility", July 1990.

2. D.J. Ribbans, memo to P.J. Armstrong, June 12, 1990.

3. G.B. Hollowy and R.L. Jones, "Welding Performance of Small Diameter Tubular Cored Wires for Semi-Automatic Welding C-Mn Steels", Welding Institue Report #391, February, 1989.

4. M.J. Tinkler and J.L. Fihey, "Development of a Prototype Robotic System for the In-Situ Repair of Hydraulic Turbine Runners, Canadian Electrical Association Project #419 G 485, February, 1989.

TABLE 1

TYPICAL CHEMICAL COMPOSITION AND MECHANICAL PROPERTIES FOR FCAW AND MCAW FILLER METAL

	HOBART FabCo 803	HOBART FabLoy 2N	COREX Verti-Cor 81-Ni2
Classification	E81T1-Ni2	E80C-Ni2	E81Ti-Ni2
Typical Weld Metal Properties (shielding gas mixture-75% Ar 25% CO2) Weld Metal Analysis (%)	0.04C, 1.05 Mn 0.03 Si, 2.50 Ni 0.00 P, 0.05 S	0.05C, 1.03 Mn 0.68 Si, 2.39 Ni	0.07C, 0.71 Mn 0.13 Si, 1.78 Ni
Tensile Strength	93,000 PSI	82,000 PSI	81,300 PSI
Yield Strength	78,000 PSI	70,000 PSI	71,010 PSI
Elongation % in 2"	22%	28%	26%
Reduction in area	67%	62%	
Condition	As Welded	Stress Relieved at 1150°F. 1 Hour	As Welded
Charpy V-notch Impact Value	44ft.lb (0°F) 32ft.lb (-45°F)	25 ft. lb (-75°F)	90 ft. lb (-40°F)

TABLE II

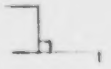
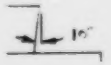
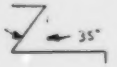
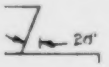
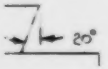
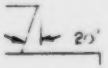
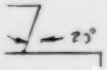
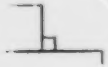
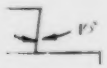
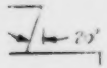
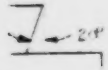
WELDING CONDITIONS AND DEPOSITION SEQUENCE FOR A TYPICAL HORIZONTAL MANUAL FCA GROOVE WELD

1.6 mm diameter Hobart FabCo 803 Filler Metal C25 Shielding Gas Mixture
CV Welding Made Slag Removal for all Weld Passes

PASS NO.	WELDING CURRENT A	VOLTAGE V	TORCH WORK ANGLE	TORCH DRAG ANGLE	ESTIMATED WELDING SPEED
1	240	24		20°	200-300 mm/min
2	270	26		20°	(8 - 12 in/min)
3	270	26		30°	"
4	270	26		30°	"
5	270	26		30°	"
6	270	26		30°	"
7	240	24		30°	"
8	270	26		30°	"
9	270	26		30°	"
10	240	24		30°	"
11	270	26		30°	"
12-14	240	24		30°	"
15	270	26		30°	"
16	240	24		30°	"
17	270	26		30°	"
18-25	210	24		30°	"

TABLE III

WELDING CONDITIONS AND EFFECTIVE THROAT THICKNESS OF FILLET/GROOVE WELDS

WELD NO.	PROCESS [1] WIRE PLATE THICKNESS	PARAMETERS	JOINT PREP	NO. OF WELD PASSES	SLAG REMOVAL	SHIELDING [2] GAS MIXTURE	EFFECTIVE THROAT THICKNESS
F1	Manual FCAW Hobart Wire, 16 mm	Fill - 300A; 200 mm/min Capping - 240A; 300 mm/min		5	all passes	C25	11.0 mm
F2	Manual FCAW Hobart Wire, 16 mm	Fill - 300A; 200 mm/min Capping - 240A; 300 mm/min		5	all passes	C25	11.5 mm
F3	Manual FCAW Hobart Wire, 16 mm	Fill - 300A; 200 mm/min Capping - 240A; 300 mm/min		6	all passes	C25	16.0 mm
F4	Manual FCAW Corex Wire, 16 mm	Fill - 240A; 230 mm/min Capping - 240A; 360 mm/min		8	all passes	C25	15.5 mm
F5	Manual FCAW Corex Wire, 16 mm	Fill - 240A; 230 mm/min Capping - 240A; 360 mm/min		8	all passes	C25	-
F6	Manual MCAW Hobart Wire, 16 mm	Fill - 250A; 250 mm/min Capping - 250A; 300 mm/min		6	no slag removal	C8	15.7 mm
F7	Manual MCAW Hobart Wire, 16 mm	Fill - 250A; 250 mm/min Capping - 250A; 300 mm/min		6	after 3 passes	C8	-
F8	Mechanized FCAW Hobart Wire, 32 mm	Fill - 300A; 300 - 500 mm/min Capping 300A; 500 mm/min		29	all passes	C25	22.0 mm
F9	Mechanized FCAW Hobart Wire, 32 mm	Fill - 300A; 300 - 500 mm/min Capping 300A; 500 mm/min		28	all passes	C25	28.0 mm
F10	Mechanized FCAW Corex Wire, 32 mm	300A 300-460 mm/min (see Table IV)		27	all passes	C25	32.0 mm
F11	Mechanized MCAW Hobart Wire, 32 mm	300 A 250 - 360 mm/min (see Table V)		26	after completion of 3, 7 and 10 weld passes	C8	33.5 mm

1) 1.6 mm diameter electrodes
2) C25 - 75% Ar 25% CO_2
   C8 - 92% Ar 8% CO_2

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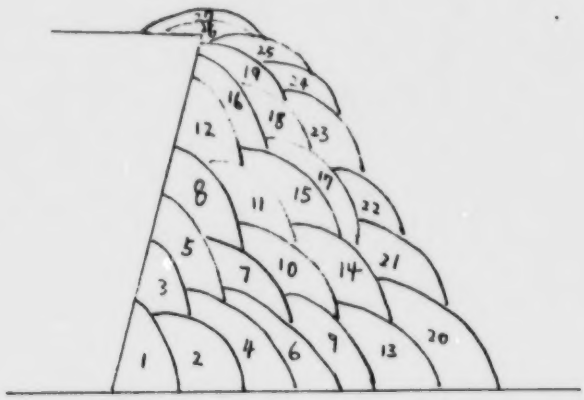
TABLE IV

DETAILED WELDING CONDITIONS AND WELD BEAD DEPOSITION SEQUENCE FOR A MECHANIZED FCA FILLET/GROOVE WELD (F10)

1.6 MM DIAM. COREX
VERTI-COR 81Ni2

C25 SHIELDING GAS
STICKOUT 20-25 MM
CV WELDING MODE
SLAG REMOVAL FOR
ALL WELD PASSES



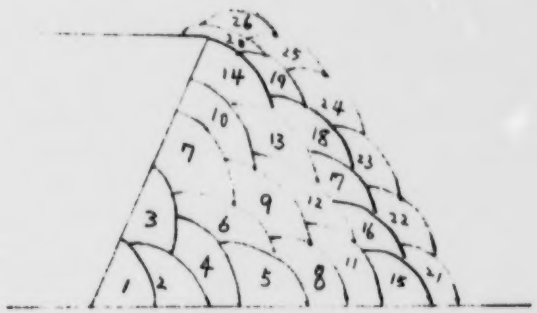
PASS NO.	CURRENT A	VOLTAGE V	TORCH WORK ANGLE FROM VERTICAL	TORCH DRAG ANGLE	WELDING SPEED MM/MIN (IN/MIN)
1-20	300	28	60°	30°	300 (12)
21-27	300	28	60°	30°	460 (18)

TABLE V

DETAILED WELDING CONDITIONS AND WELD BEAD DEPOSITION SEQUENCE FOR A MECHANIZED MCA FILLET/GROOVE WELD (F11)

1.6 MM DIAM. HOBART FABLOY 2N FILLER METAL

C8 SHIELDING GAS MIXTURE
STICKOUT 20-25 MM
PULSED CURRENT
SLAG REMOVAL AT WELD PASS NO. 3, 7 AND 10



PASS NO.	CURRENT A	VOLTAGE V	TORCH WORK ANGLE FROM VERTICAL	TORCH DRAG ANGLE	WELDING SPEED MM/MIN (IN/MIN)
1-7	300	28	60°	30°	250 (10)
8-10	300	28	60°	30°	300 (12)
11-14	300	28	60°	30°	300 (12)
15-26	300	28	60°	30°	360 (14)

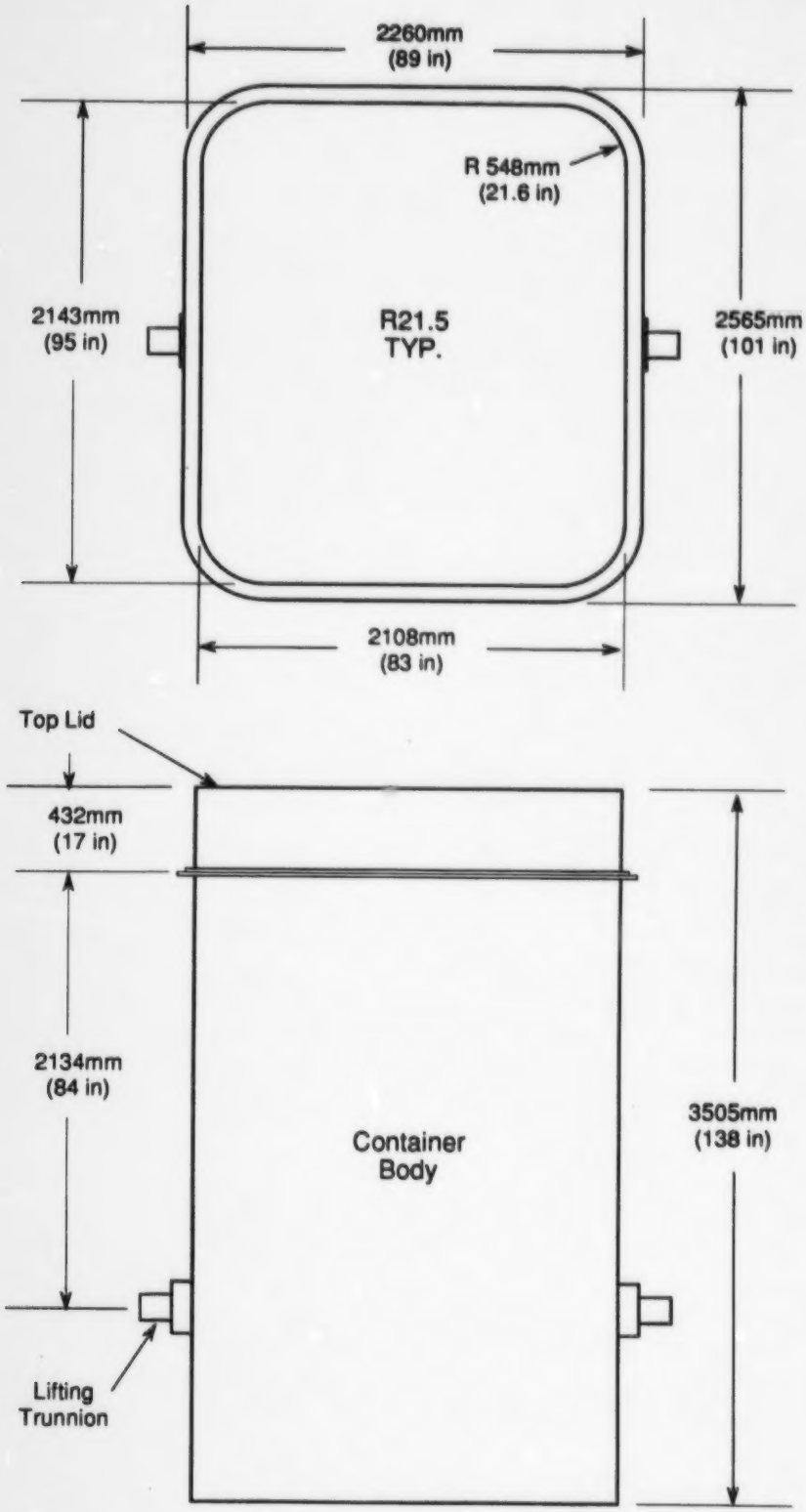


FIGURE 1

SCHEMATIC DIAGRAM OF THE CONCRETE INTEGRATED CONTAINER

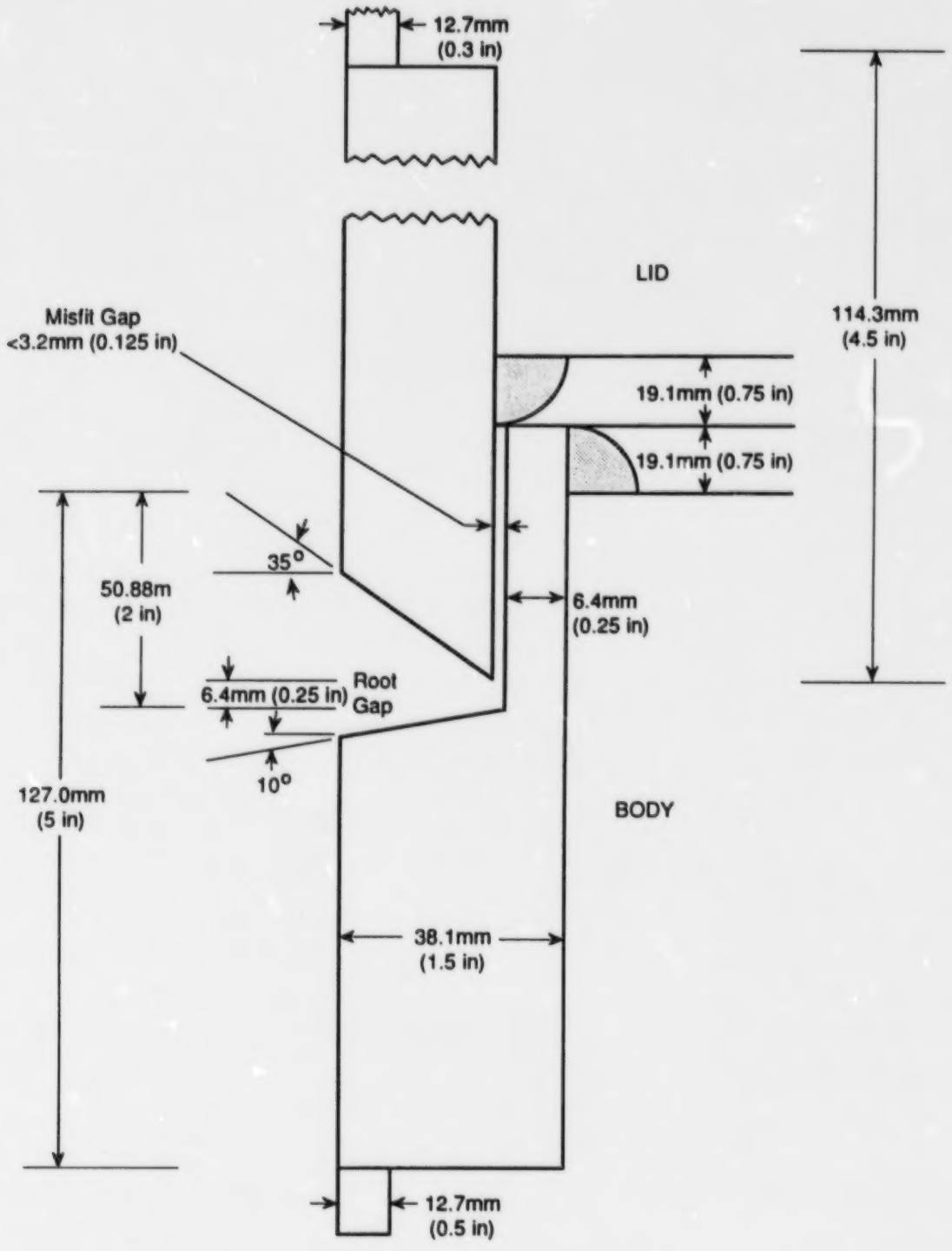


FIGURE 2

SCHEMATIC DIAGRAM OF HORIZONTAL GROOVE WELD JOINT IN TYPE A LID CLOSURE ASSEMBLY

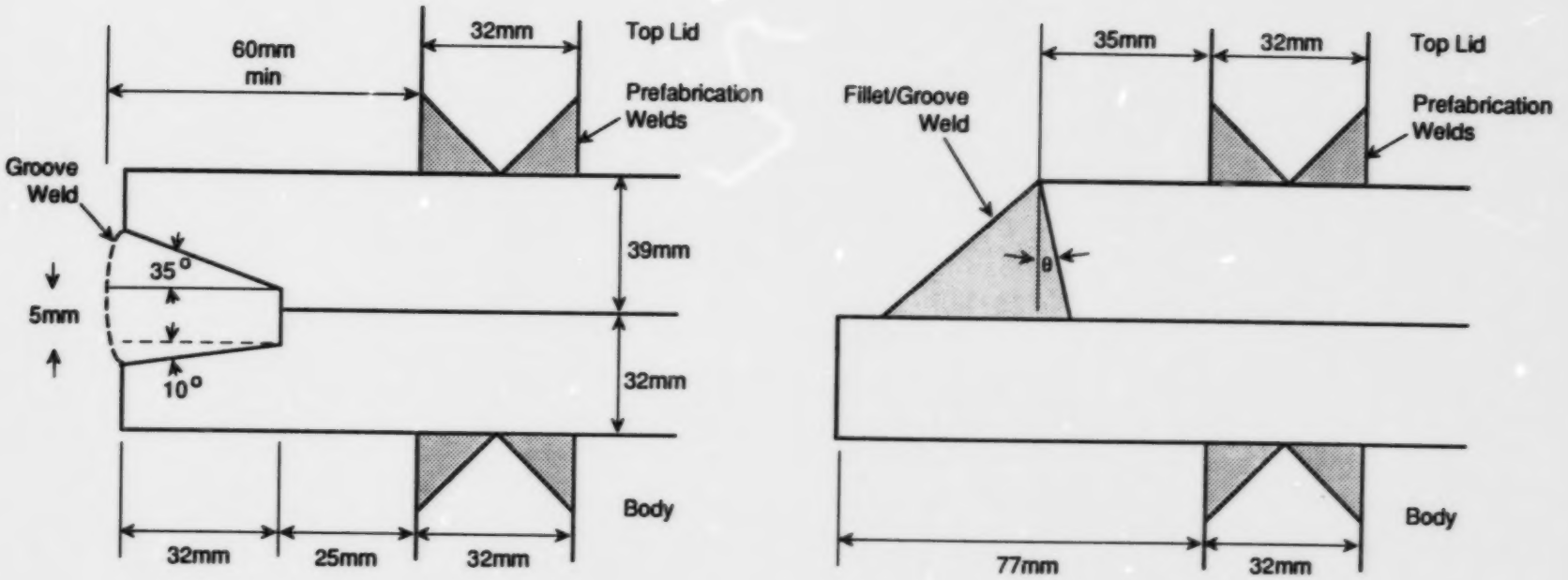


FIGURE 3

SCHEMATIC DIAGRAM OF HORIZONTAL WELD JOINT DESIGNS IN TYPE B LID CLOSURE ASSEMBLY

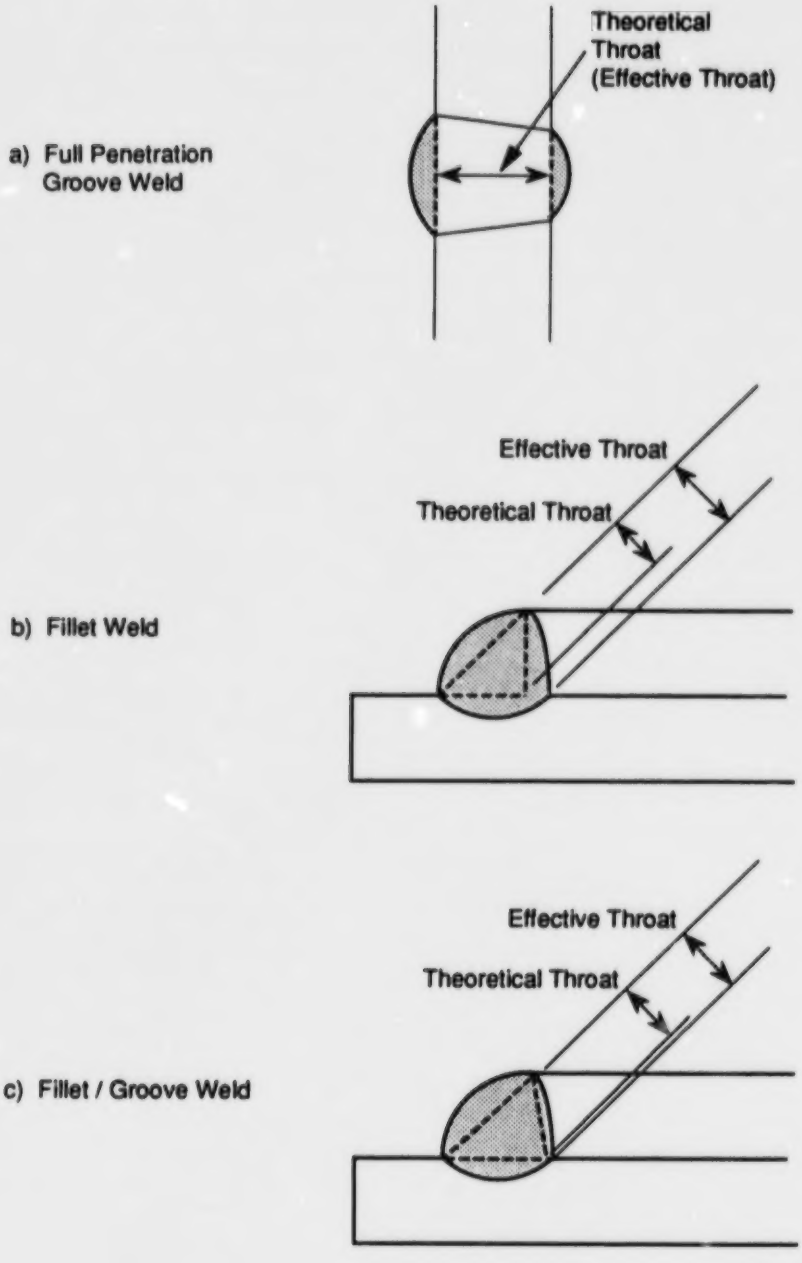
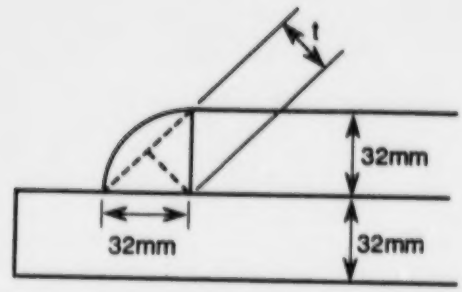
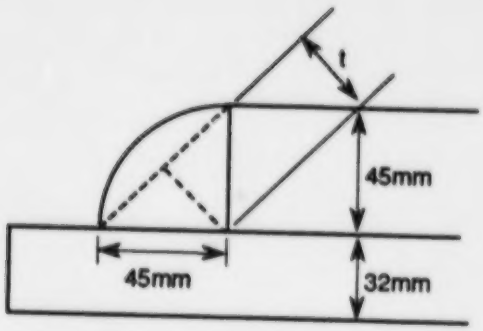


FIGURE 4

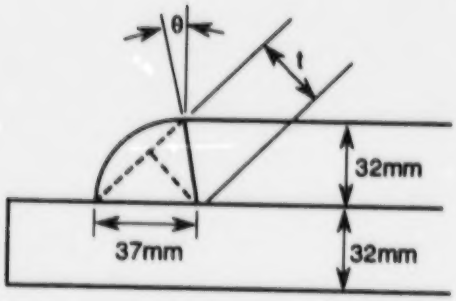
DEFINITIONS OF EFFECTIVE THROAT AND THEORETICAL THROAT



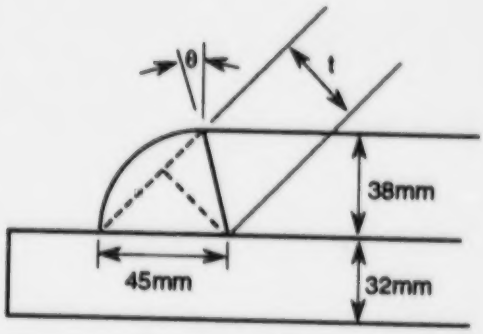
a) θ = 0°
t = 22.4mm



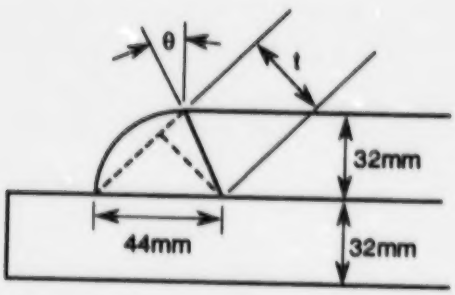
d) θ = 0°
t = 32mm



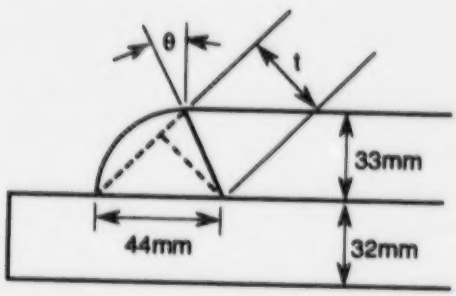
b) θ = 10°
t = 27mm



e) θ = 10°
t = 32mm



c) θ = 20°
t = 31mm



f) θ = 20°
t = 32mm

FIGURE 5

SCHEMATIC DIAGRAMS SHOWING THEORETICAL THROAT THICKNESS IN VARIOUS FILLET / GROOVE WELD JOINTS

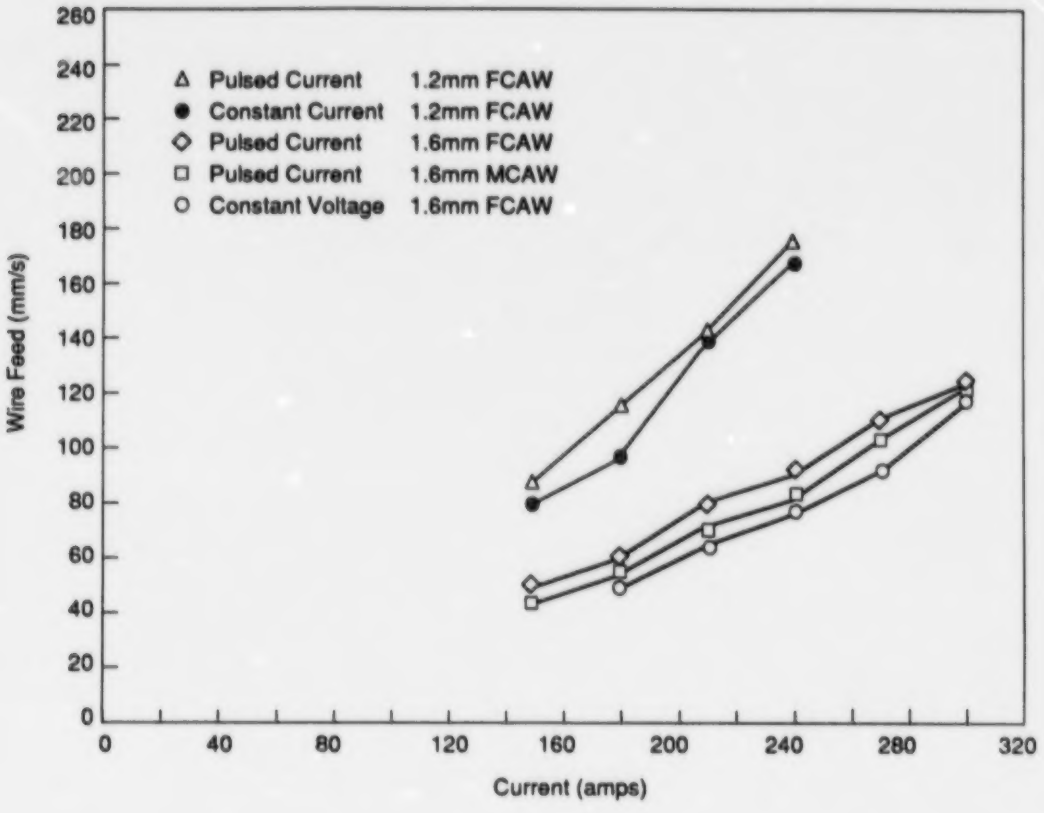


FIGURE 6

BURNOFF CURVES AND OPERATING CURRENT RANGE FOR FCAW AND MCAW ELECTRODES

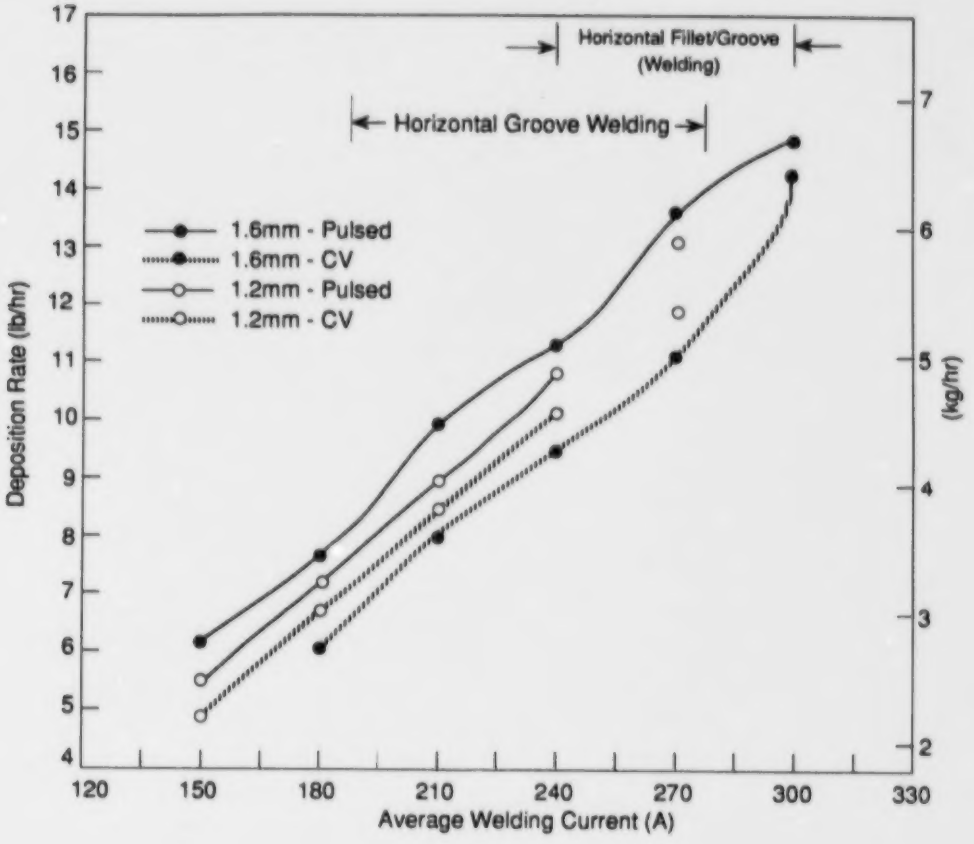
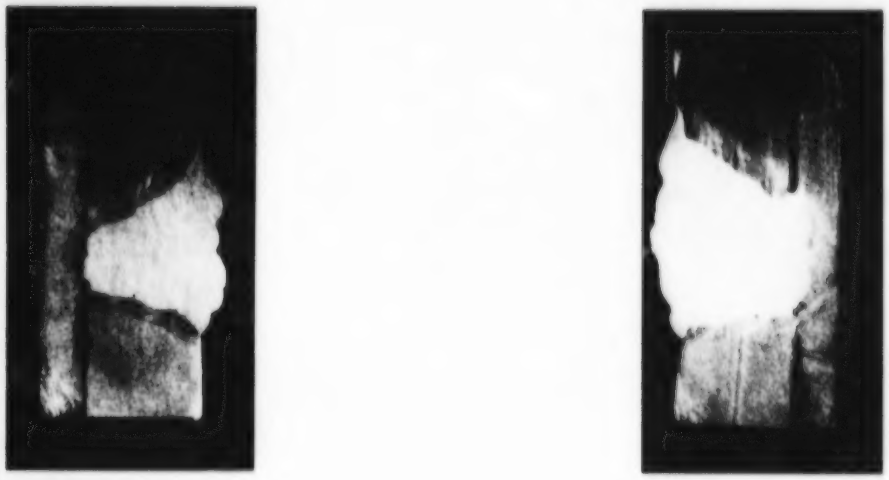


FIGURE 7

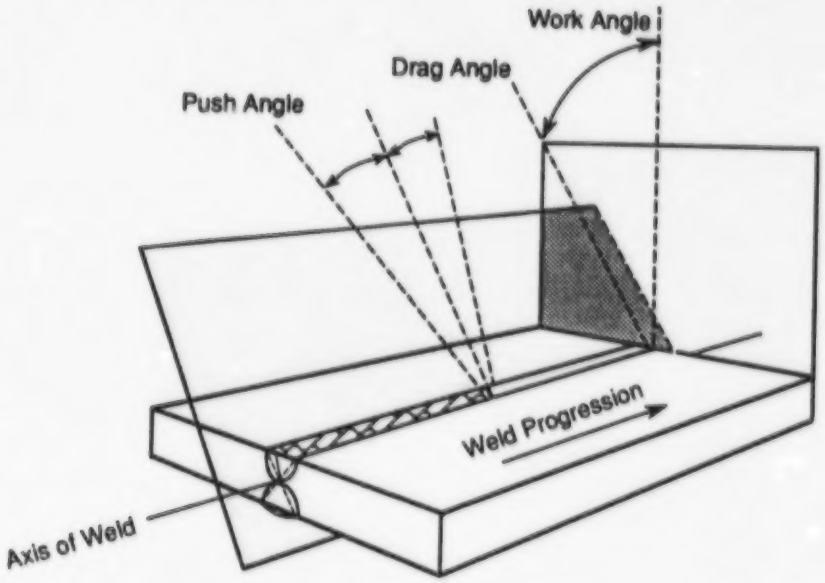
WELD METAL DEPOSITION RATES FOR 1.2mm AND 1.6m DIAMETER FCAW FILLER METAL



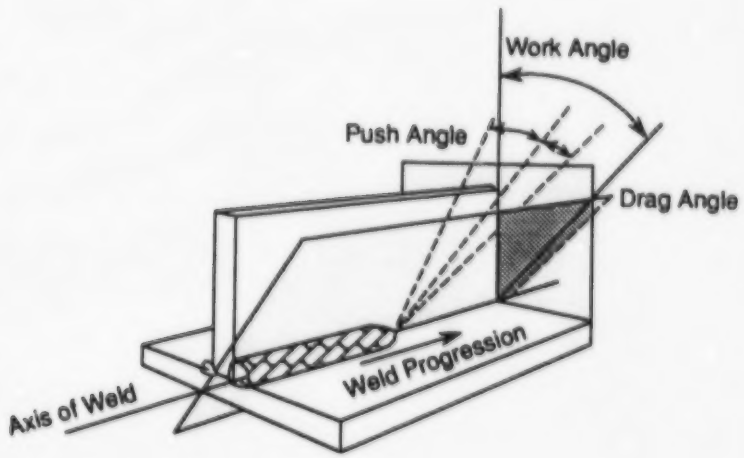
a) 5 mm root gap b) 15 mm root gap

Figure 8 Cross Sections of horizontal flux-cored arc groove welds in 16 mm thick carbon steel plates (mag 1X)

Figure 9 Cross Section of a flux-cored arc horizontal groove weld in 32 mm thick carbon steel plates (mag 1X)



Groove Weld



Fillet Weld

FIGURE 10

DEFINITIONS FOR DRAG ANGLE, PUSH ANGLE AND WORK ANGLE

Figure 11 Photograph showing a Needle Descaler for slag removal

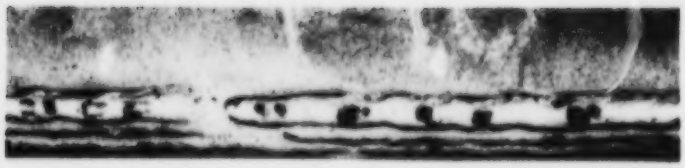
a) Sample F1 - 0°bevel

b) Sample F2 - 10° bevel

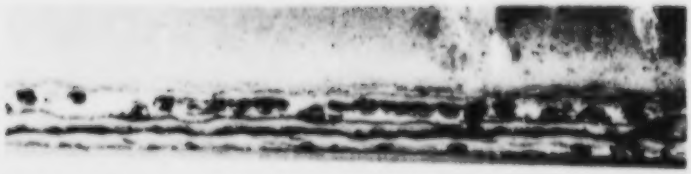
c) Sample F3 - 35° bevel

d) Sample F4 - 20° bevel

Figure 12 Cross Sections of flux-cored arc horizontal fillet/ groove welds in 16 mm thick carbon steel plates (mag 1X)



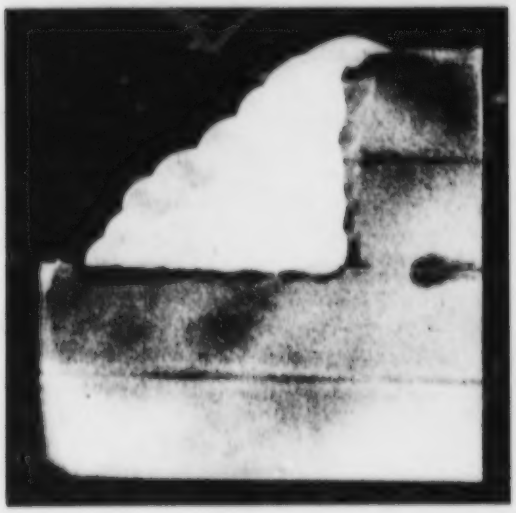
a) F7 - slag removed after 3 weld passes



b) F6 - no slag removal

Figure 13 Surface view of metal-cored arc horizontal fillet/grove welds showing islands of slag on weld surface (mag 3X)

Figure 14 Cross section of a metal-cored arc horizontal fillet/grove weld (F7) in 16 mm thick carbon steel plates (mag 3.5X)



a) Sample F8 - 0° bevel

b) Sample F9 - 10° bevel

Figure 15 Cross sections of mechanized flux-cored arc horizontal fillet/grove welds in 32 mm thick carbon steel plates (F8 and F9) (mag 1X)

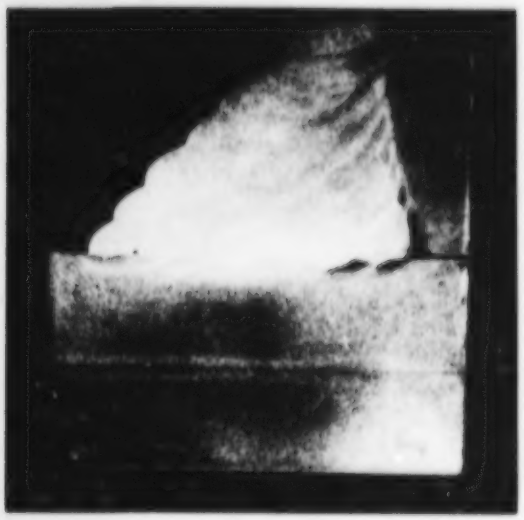


Figure 16 Cross section of a mechanized FCAW horizontal fillet/groove weld in 32 mm thick carbon steel plates (F10 - 20° bevel) (mag 1X)

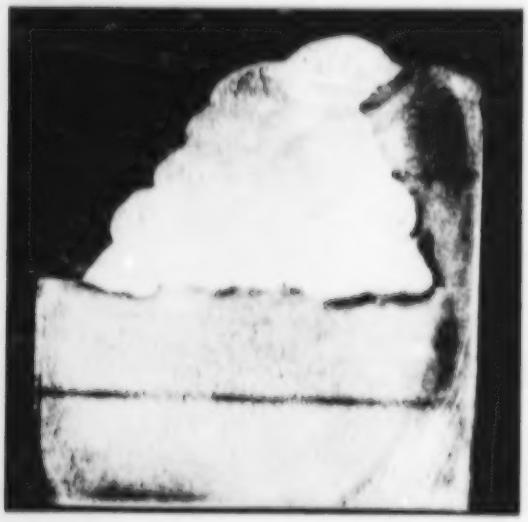


Figure 17 Cross section of a mechanized MCAW horizontal fillet/groove weld in 32 mm thick carbon steel plates (F11 - 20° bevel) (mag 1X)